



Single skyrmion detection using electrical transport in Pt/Co/Ir multilayer disc

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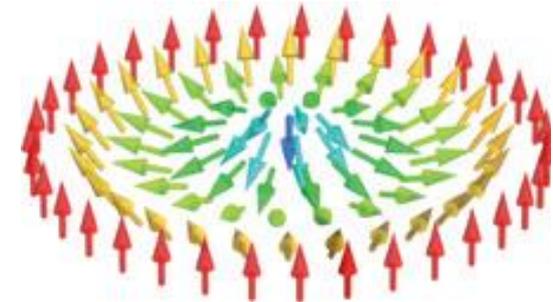


Room Temperature Skyrmions

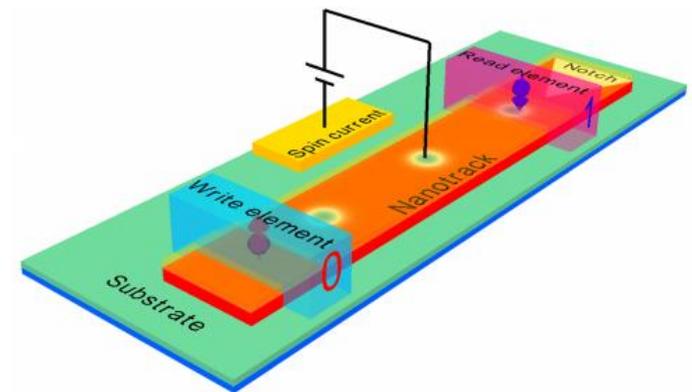
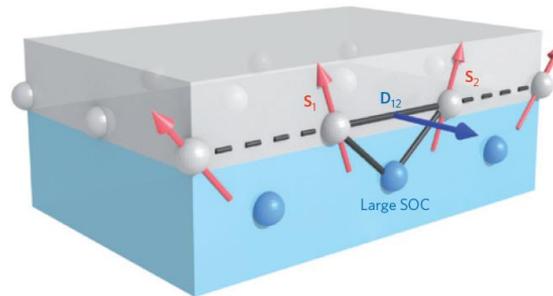
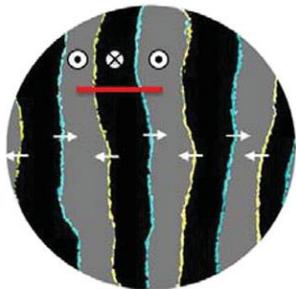


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- Nanoscale stable magnetic quasi particles
- Potential for novel information storage
- Movable by low current densities
- Dzyaloshinskii-Moriya interaction at the interface between a ferromagnet and a heavy metal
- Inversion symmetry breaking
- Magnetization rotates around DMI vector
- Chiral DW



[2] A. Fert, et al. Nature Nanotech. 8 152 (2013).



Zhang et al Scientific Report 5 7643 (2014)



Cu(100)/Fe/Ni
Chen PRL 110, 177204
(2013)

$$E_{DM} = \mathbf{D} \cdot \mathbf{S}_1 \times \mathbf{S}_2$$

Chiral Domain Walls



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OUT OF PLANE EASY AXIS

DOMAIN WALL

- Two possible magnetization re-orientation

BLOCH:

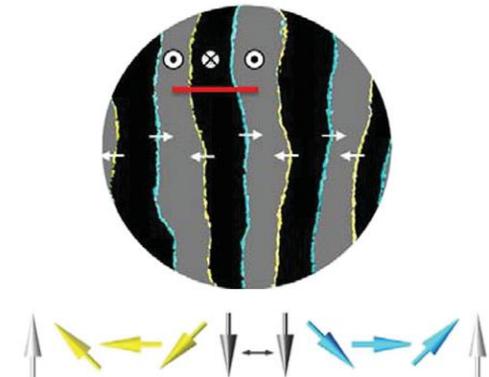
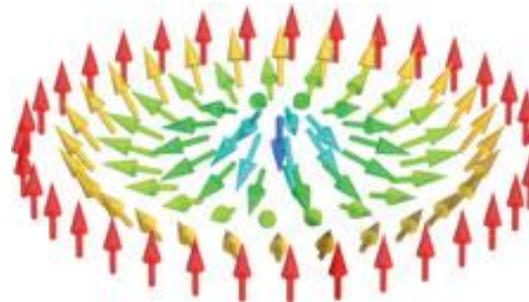
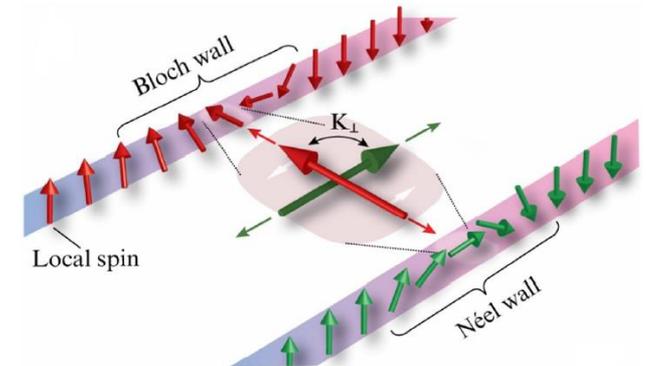
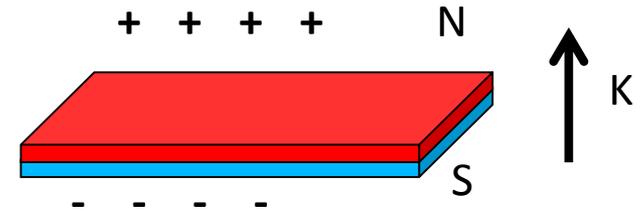
- perpendicular to the magnetization plane
- Low magnetostatic energy

NÉEL:

- Parallel to the magnetization plane
- Two possible chiralities

INFLUENCE OF DMI

- Néel domain wall
- Fixed chirality



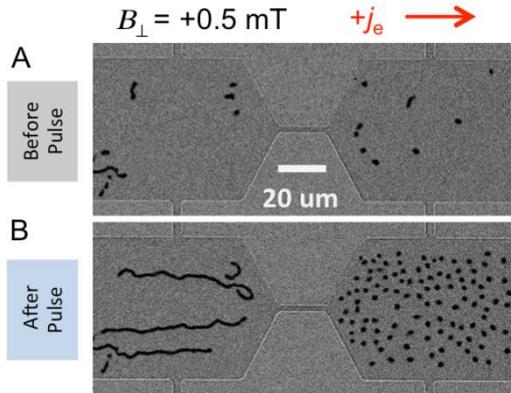
Cu(100)/Fe/Ni
Chen PRL 110, 177204
(2013)

Room temperature chiral magnetic skyrmions



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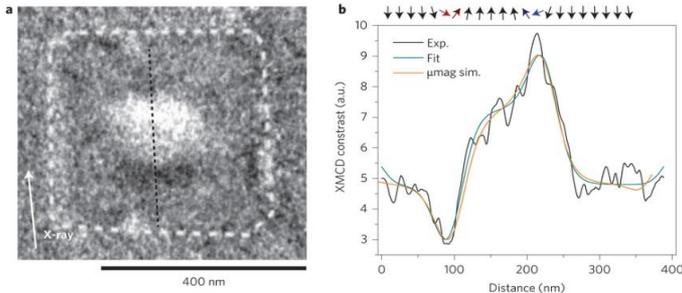
TRILAYER



$D_S = 700-2000 \text{ nm}$

Ta/CoFeB/TaOx

Jiang et al. Science (2015)

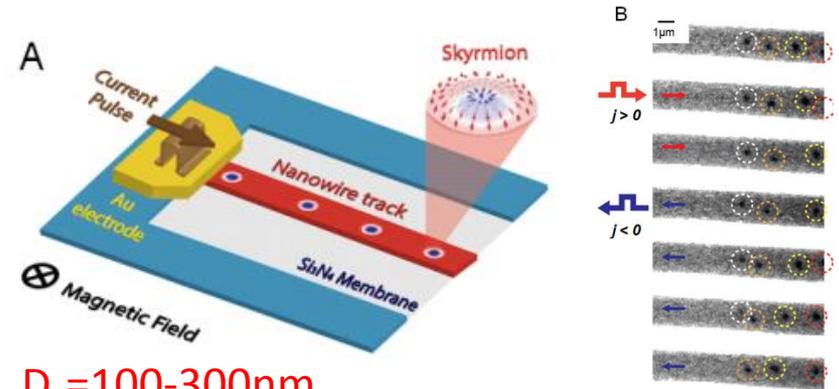


$D_S = 150 \text{ nm}$

Pt/Co/MgO

Boulle et al. Nature Nanotech. (2016)

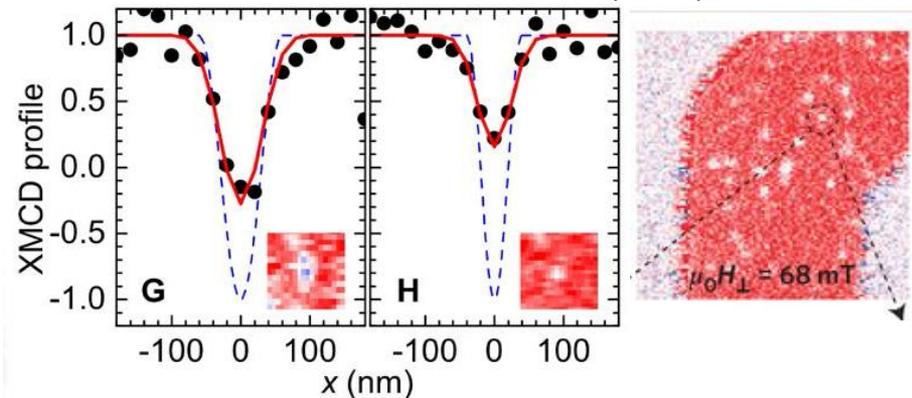
MULTILAYER



$D_S = 100-300 \text{ nm}$

{Pt/Co/Ta} × N

Woo et al. Nature Materials (2016)



$D_S = 30-90 \text{ nm}$

{Pt/Co/Ir} × N

Moreau-Luchaire et al. Nature Nanotech. (2016)

Field dependence of skyrmion diameter

- [Pt(2.3 nm)/Co(0.7 nm)/Ir(0.5 nm)]_{x10}
- Scanning transmission X-ray microscopy
- Pinning

Electrical detection of a single skyrmion

- [Pt(1.0 nm)/Co(0.5 nm)/Ir(0.5 nm)]_{x10}
- Scanning transmission X-ray microscopy
- In situ transport measurements
- Skyrmion detection

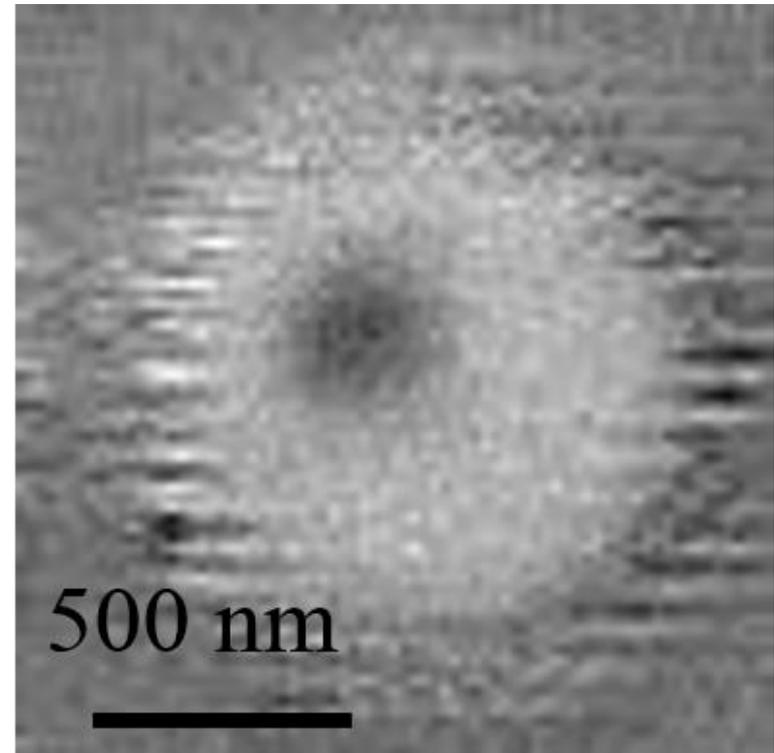
Magnetic Imaging



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STXM AT POLLUX/PSI

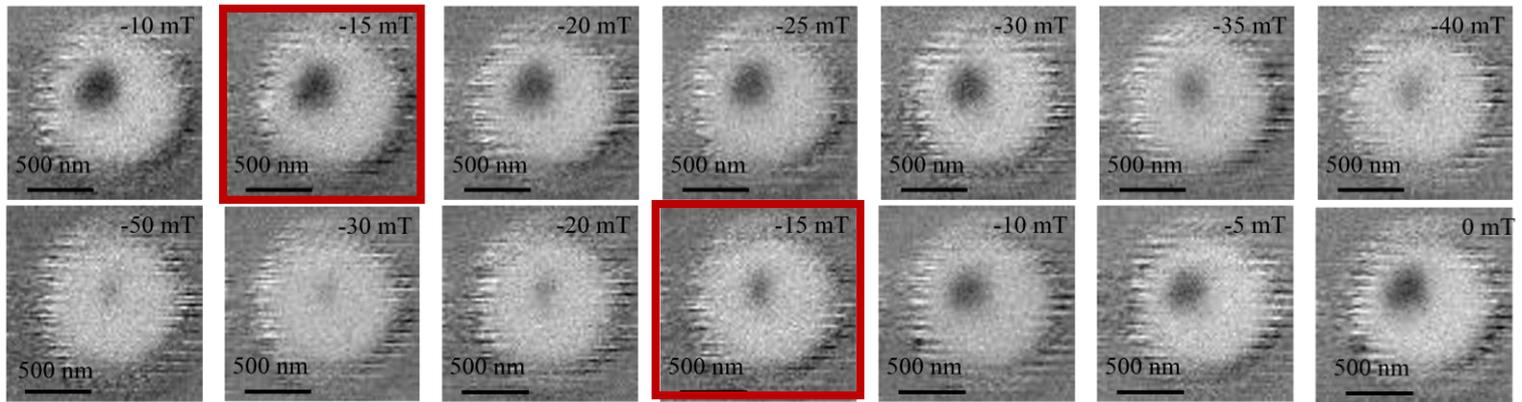
- Co L3 edge (779.5 eV)
- Room temperature
- Field applied out-of-plane
- X-ray absorption proportional to out-of-plane magnetization
- Dark and bright contrast represents oppositely out-of-plane magnetized regions
- Skyrmion are observed



Diameter Evolution

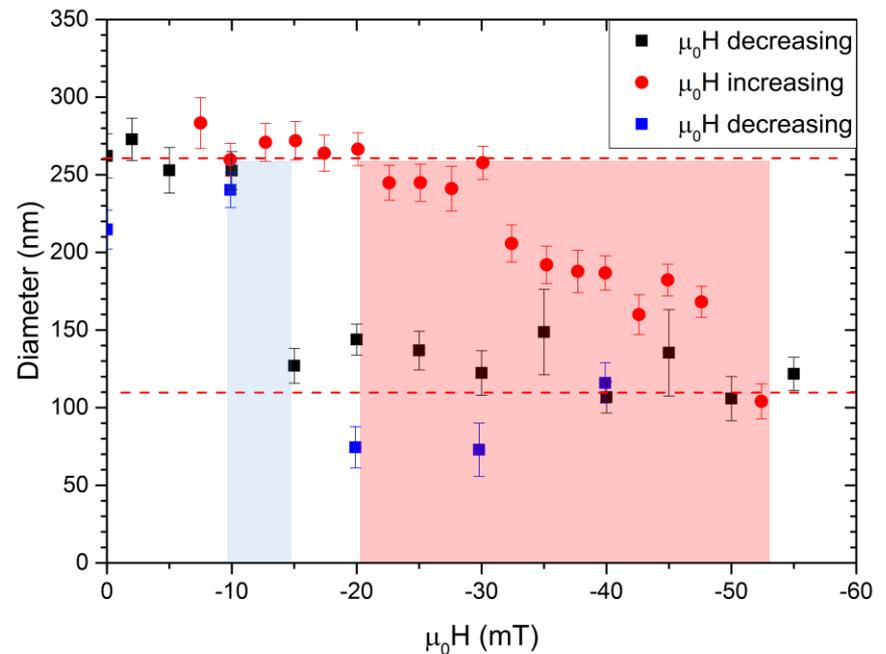


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HYSTERETIC EXPANSION

- Stable skyrmion at RT and 0 mT
- Slow decrease > -20 mT
- Step like expansion < -10 mT
- Diameter varies from 260 nm to 110 nm
- Indication of pinning

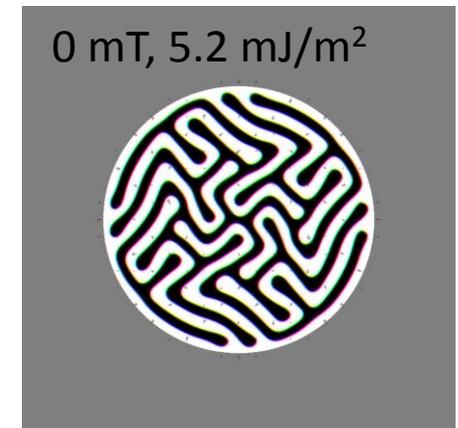
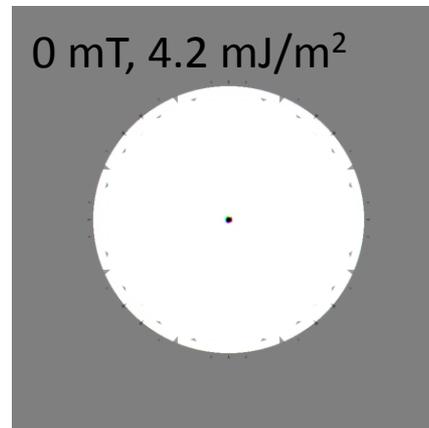
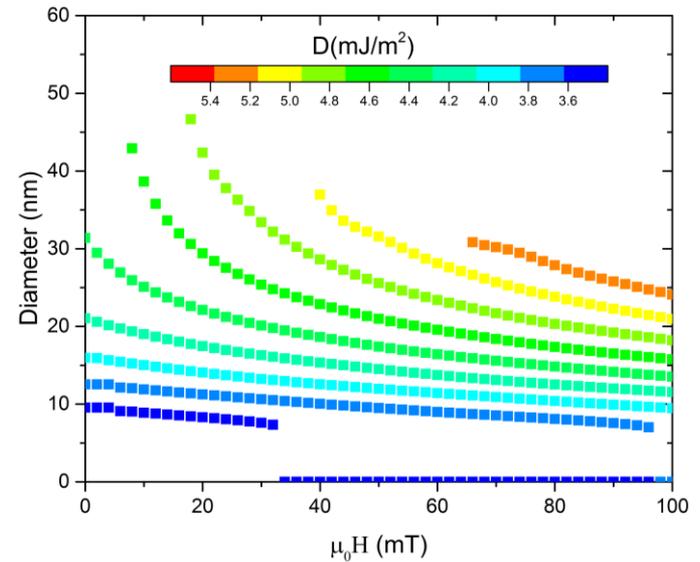


Disorder Free Simulation



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- Single 0.7 nm Cobalt layer
- Uniform magnetization below 3.6 mJ/m²
- DW energy $\sigma = 4V(AK_{\text{eff}}) - \pi D$
- 0 mT skyrmion
- $D > D_c$ Cycloidal domain state
- No 0 mT skyrmion
- Simulation diameter \ll measured diameter
10-47nm \ll 110nm-260nm
- No field hysteresis



Micromagnetic Simulation



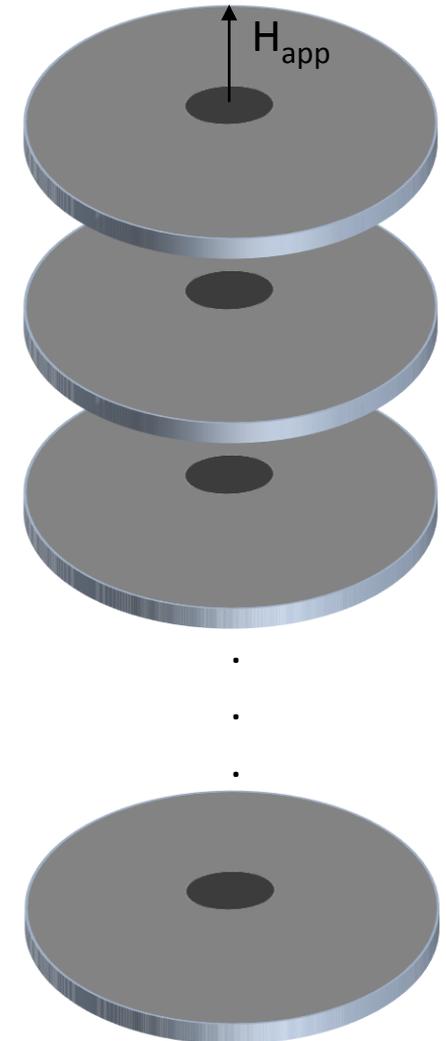
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MEASURED

- $M_{\text{sat}} = 1.2 \pm 0.1 \text{ MA/m}$
- $A = 15 \pm 1 \text{ pJ/m}$
- $K_{\text{eff}} = 0.66 \text{ MJ/m}^3$
- $D = 1.48 \text{ mJ/m}^2$ (Brillouin light scattering)

SIMULATION

- MuMax³
- 1000 nm cobalt disc
- 10 repeats of 0.7 nm Cobalt layers separated by 2.8 nm
- Mesh size (x, y, z): (1.3 nm, 1.3 nm, 0.7 nm)
- Diameter evolution with increasing field



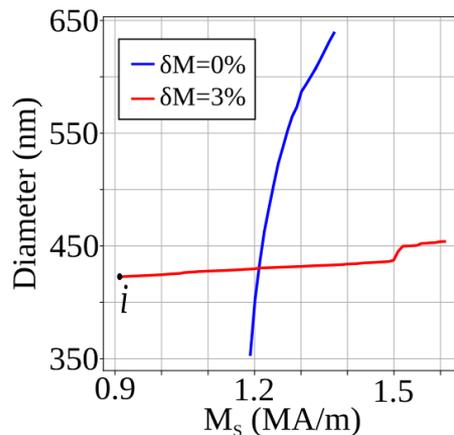
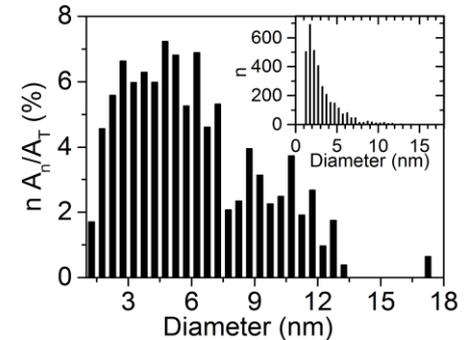
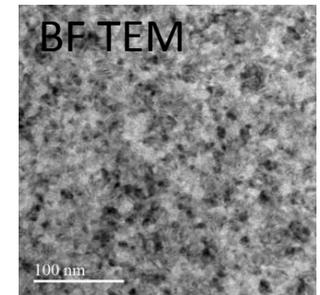
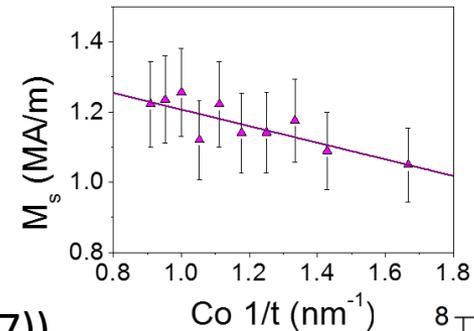
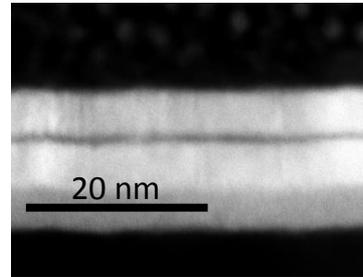
Disordered Simulation



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DISORDER

- Modulate thickness
- Average M_s with standard deviation of $\delta M/M$, 3%
- 10 nm grain size (J.V. Kim APL **110** 132404 (2017))
- Stabilizes skyrmion
- Domain boundary found in regions of high M_s i.e. thicker regions



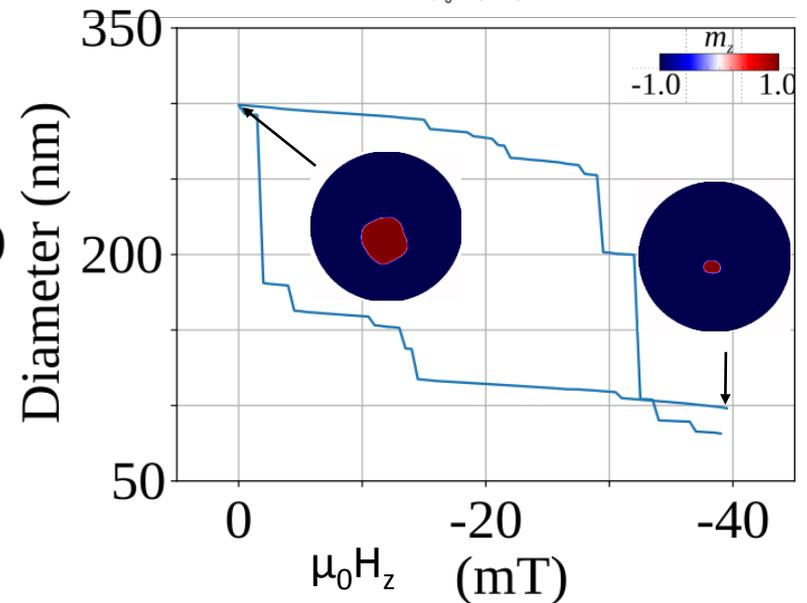
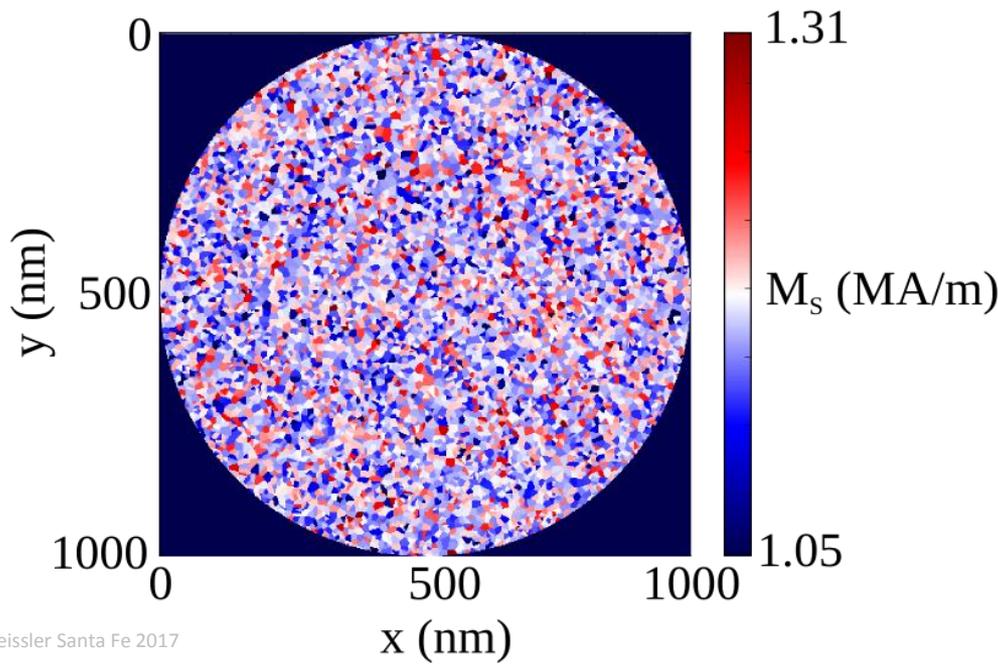
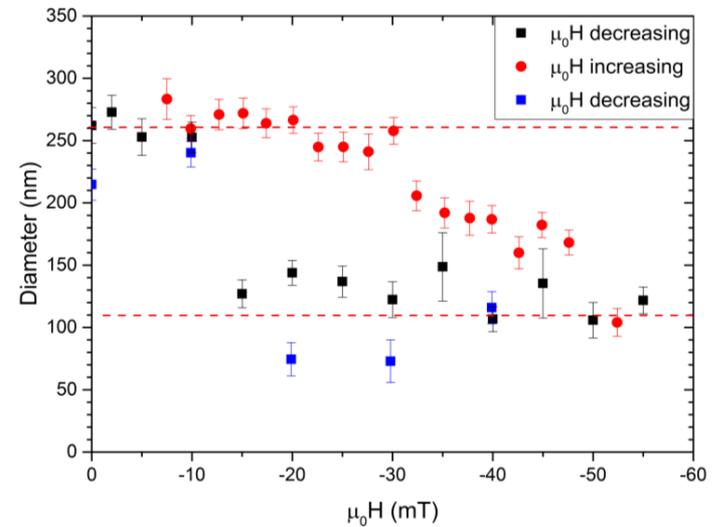
Disordered Simulation



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FIELD DEPENDENCE

- Diameter field history dependent
- Diameter decreases step like
- Simulation and experiment follow same trend

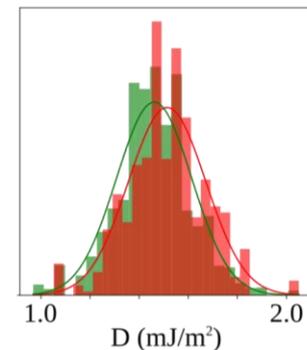
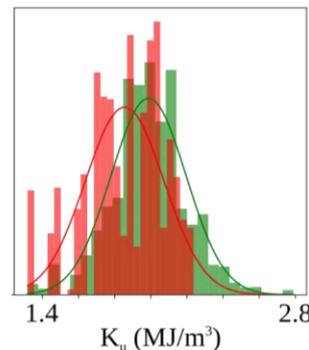
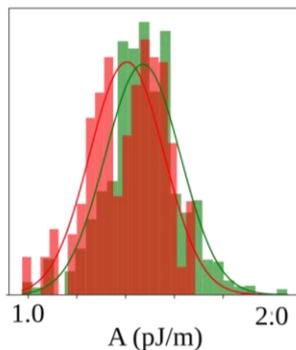
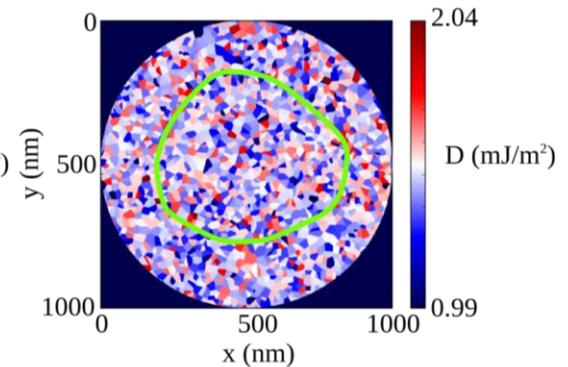
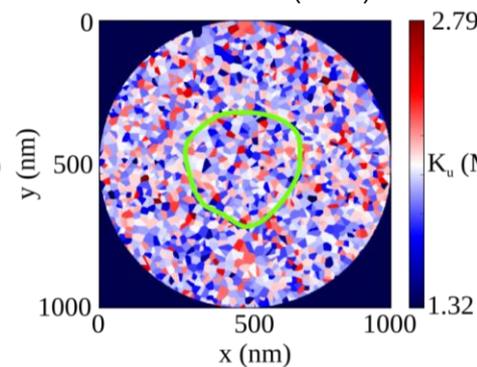
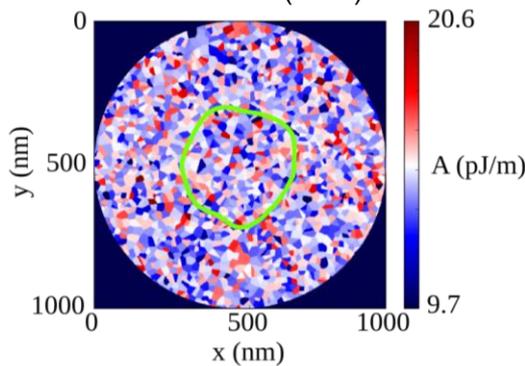
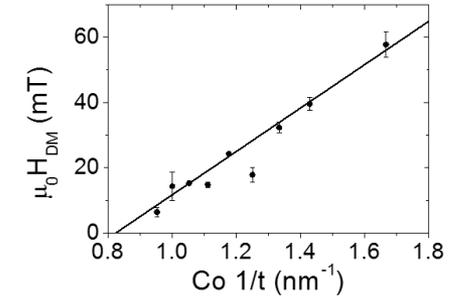
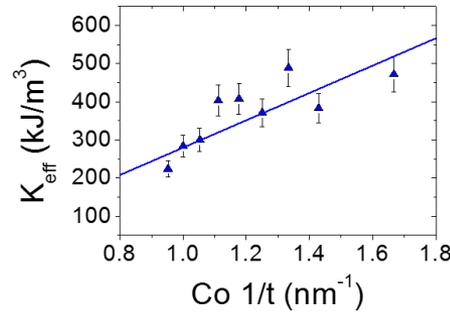
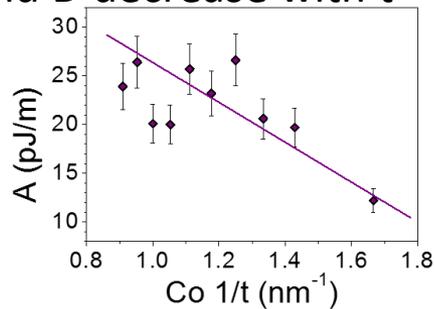


Disordered Simulation



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- A increases with t
- K_{eff} and D decrease with t

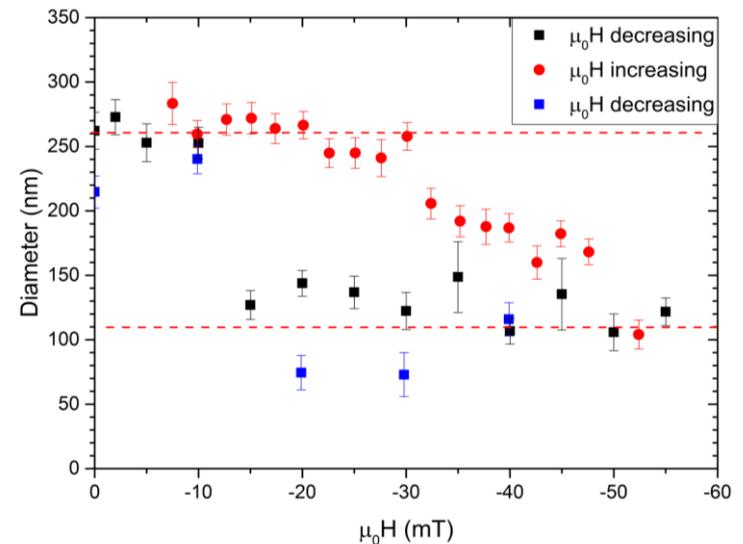
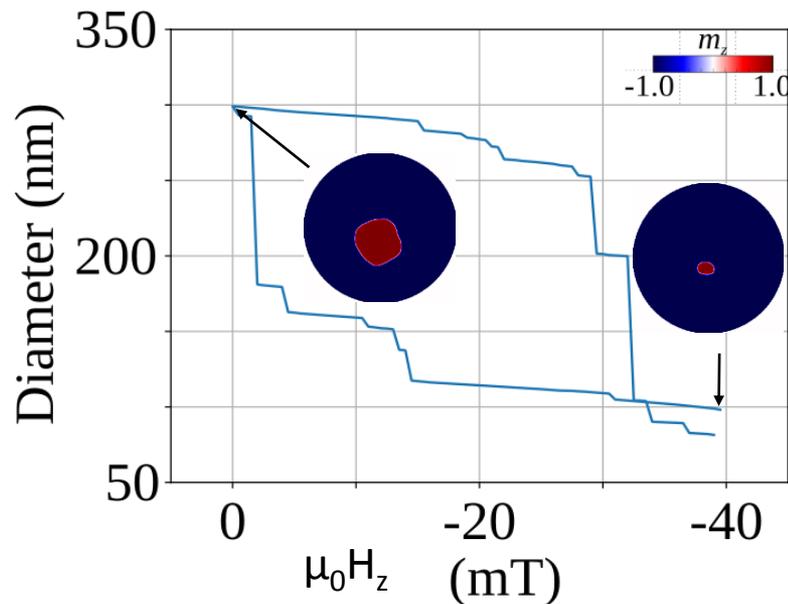
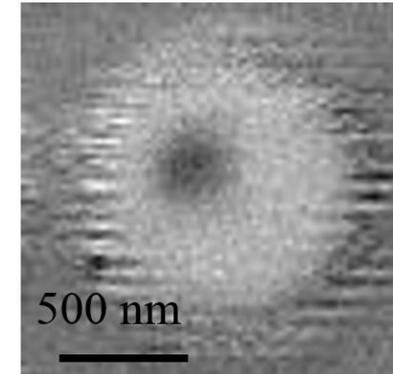


Conclusion



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- Sputtered Pt/Co/Ir multilayers
- Observed skyrmion
- Pinning plays crucial role in stabilizing skyrmion
- Hysteretic field dependence
- Disorder needs to be taken into account in simulations
- ArXiv 1706.01065



Field dependence of skyrmion diameter

- [Pt(2.3 nm)/Co(0.7 nm)/Ir(0.5 nm)]_{x10}
- Scanning transmission X-ray microscopy
- Pinning

Electrical detection of a single skyrmion

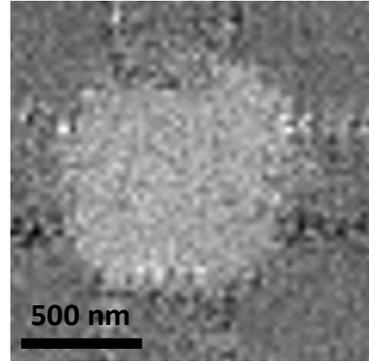
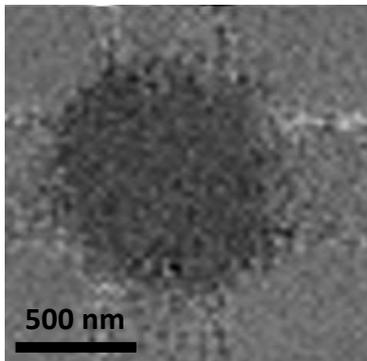
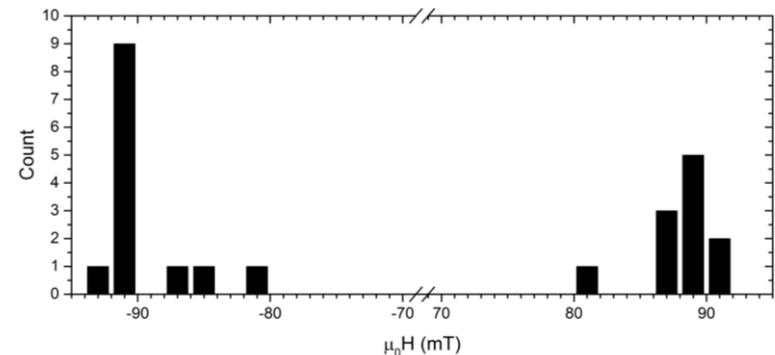
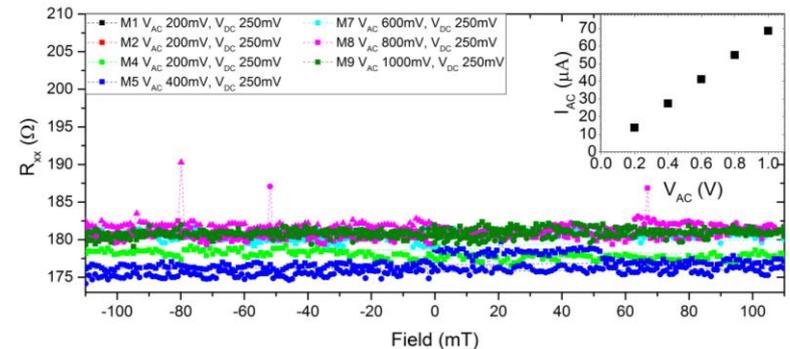
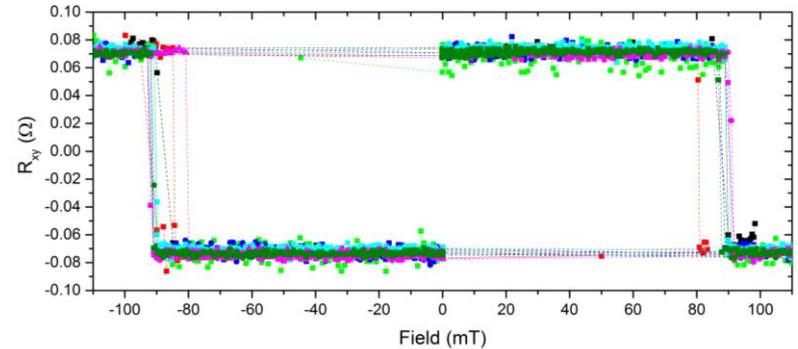
- [Pt(1.0 nm)/Co(0.5 nm)/Ir(0.5 nm)]_{x10}
- Scanning transmission X-ray microscopy
- In situ transport measurements
- Skyrmion detection

Field Driven Reversal



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- Out of plane field applied
- XMCD contrast
BLACK = +90 mT
WHITE = -90 mT
- Clear Hall signal
- No features in the MR
- Linear IV dependence
- No multi domain state observed
- H_C centred about 89 mT
- Nucleation field high
50 $\mu\text{m/s}$ domain wall speeds
(Hrabec PRB **90** 020402(R),2014)



Current Driven Reversal

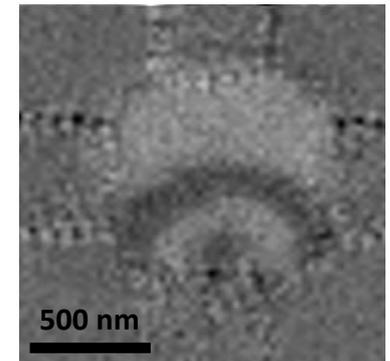
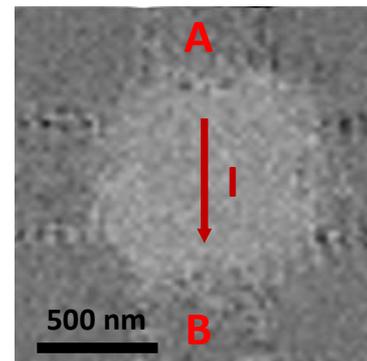
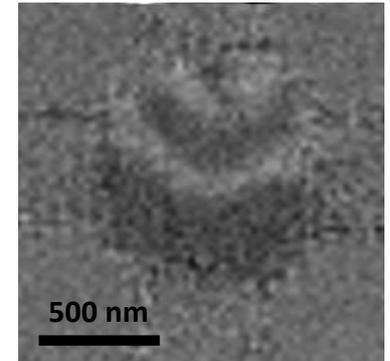
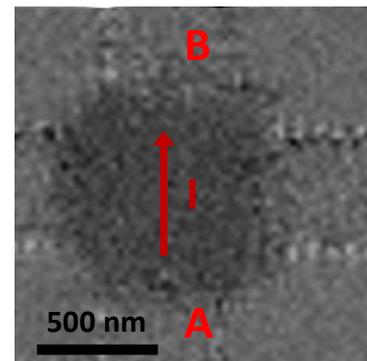
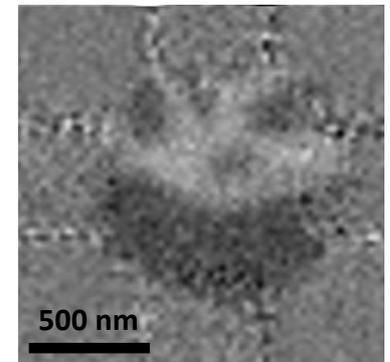
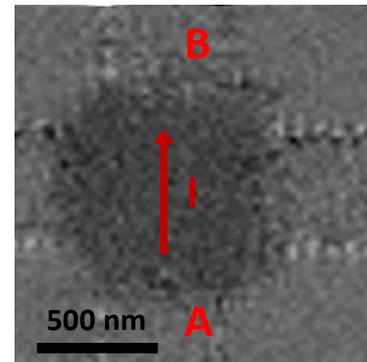


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- Disc is initially saturated, ± 100 mT
- Field is removed, 0 mT
- Five 5 ns 0.5 V pulses separated by 200 ns

$$J \sim 7 \times 10^{11} \text{ A/m}^2$$

- Current direction A to B
- Magnetic domains are nucleated

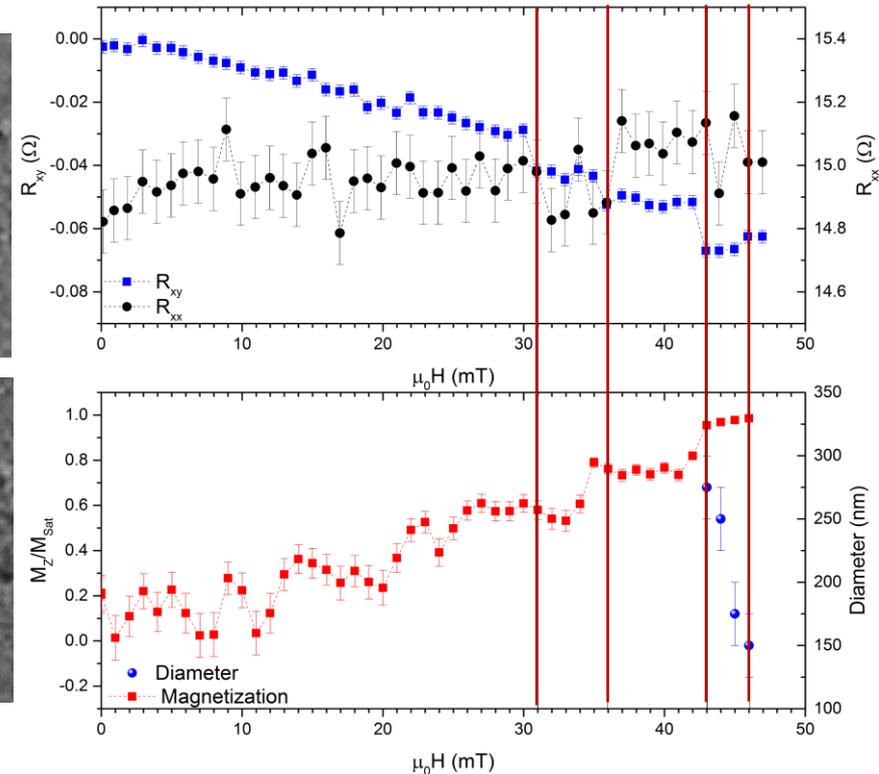
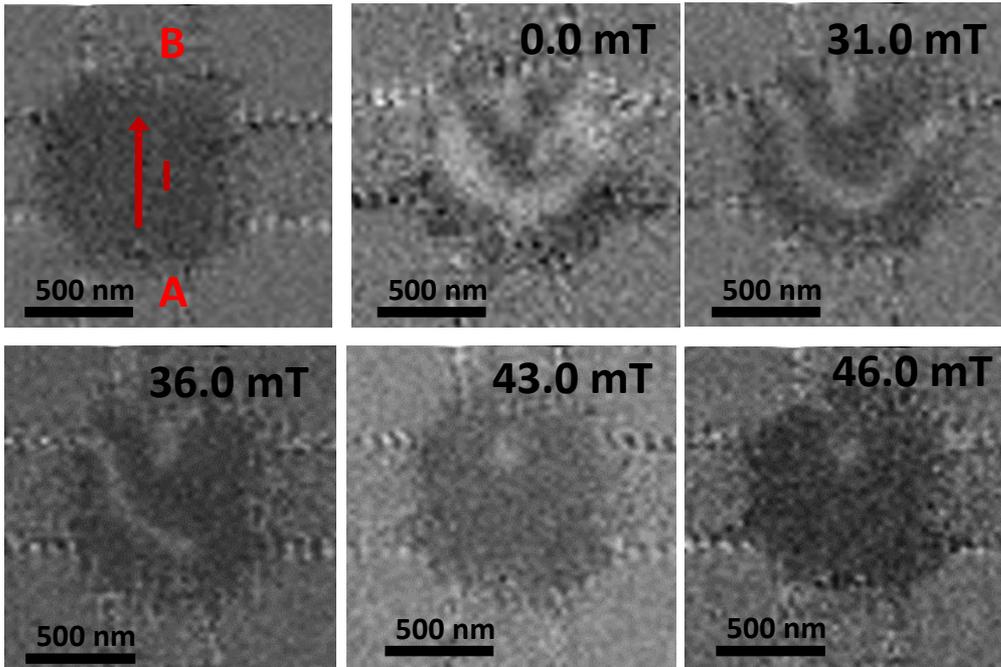


Skyrmion Creation



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- Disc is initially saturated, +100 mT
- Current direction A to B
- Applied +ve out of plane field
- Can stabilize skyrmions
- Can change the diameter

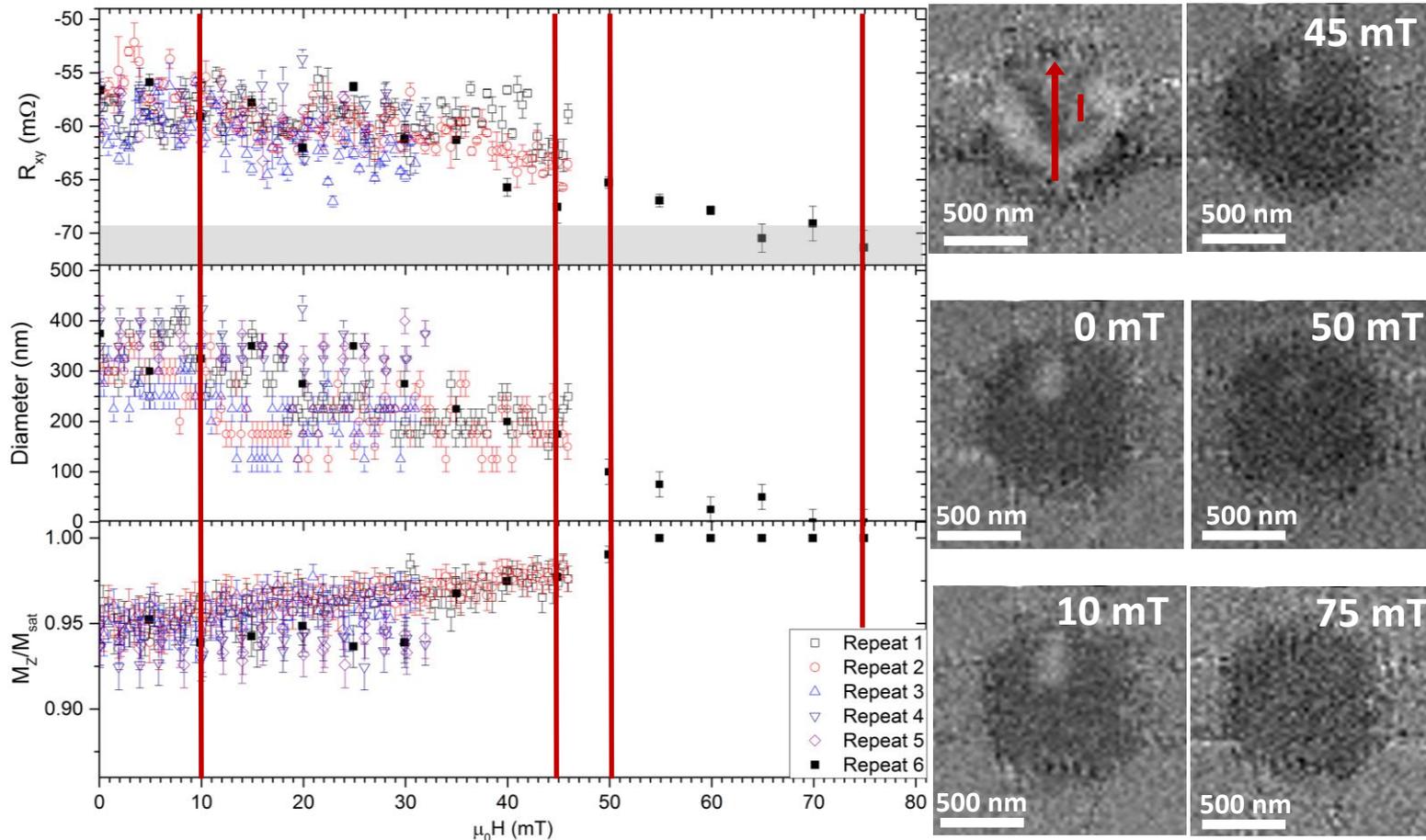


Single Skyrmion Detection



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- Return to 0 mT - 300 nm Skyrmion
- Increase field – shrinks skyrmion
- Resistance follows diameter

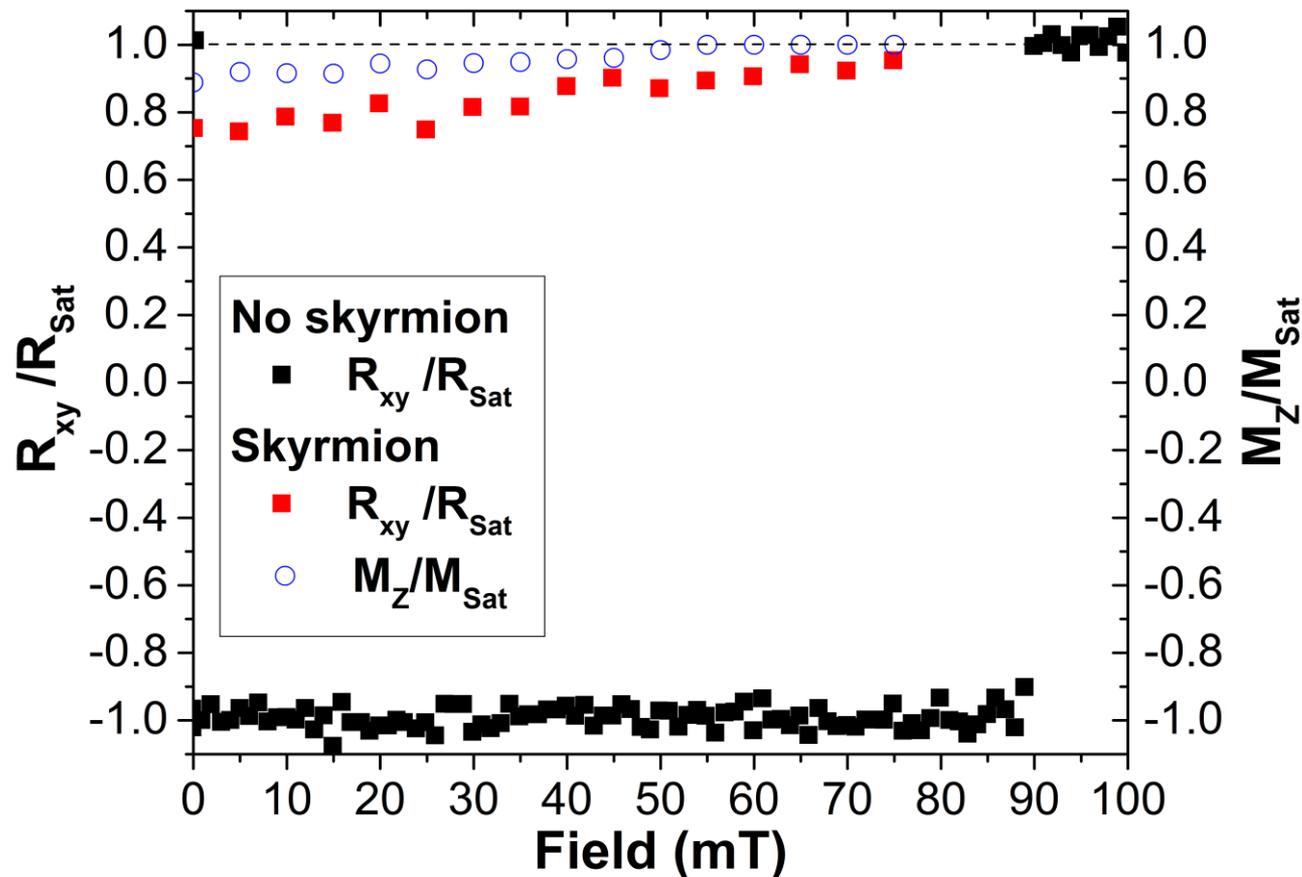


Single Skyrmion Detection



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- Normalise resistance and magnetisation
- 12 % change in the Hall resistance when skyrmion is present

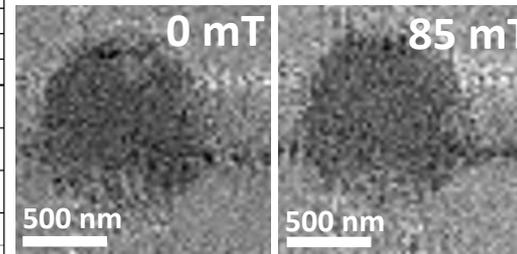
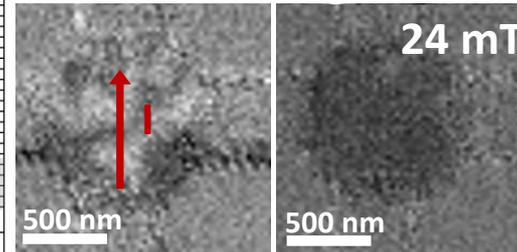
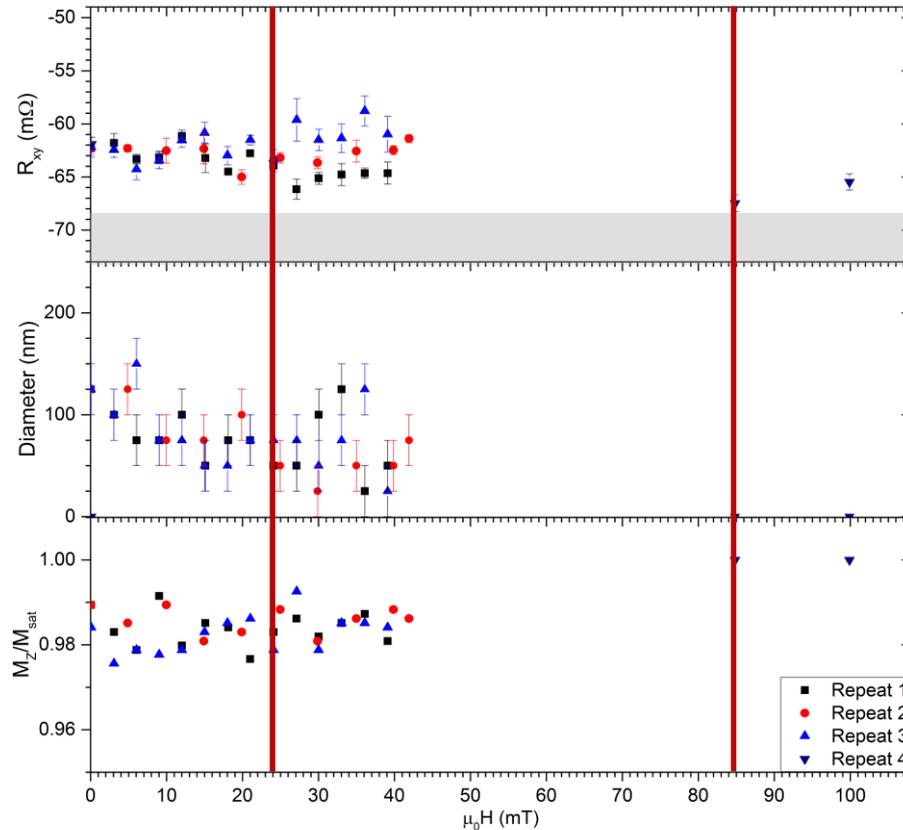


Reproducibility



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- Create domain state
- Apply field – Creates skyrmion
- Shrink skyrmion with field
- Skyrmion measurable down to 50 nm

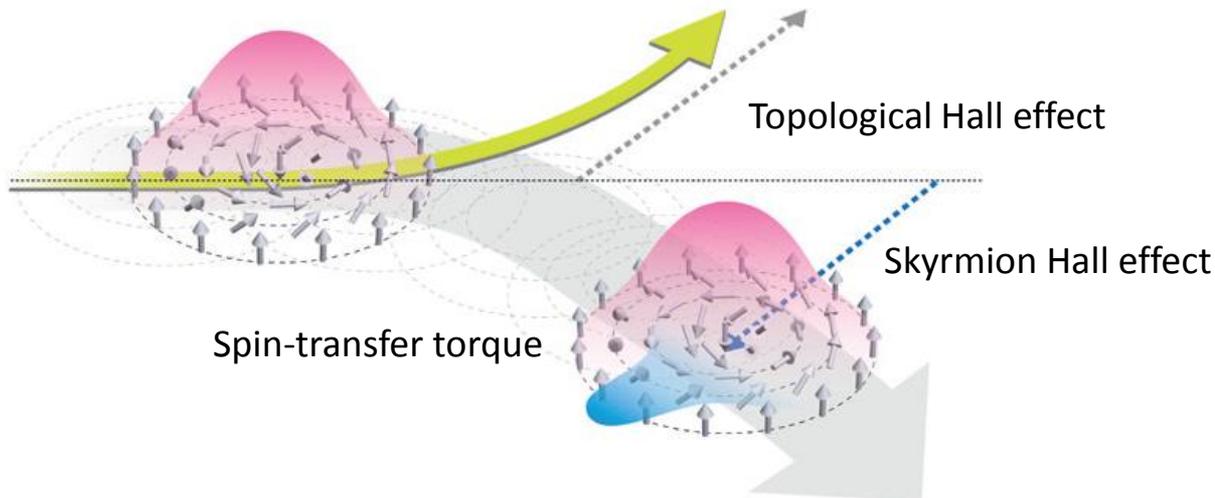


Topological Hall

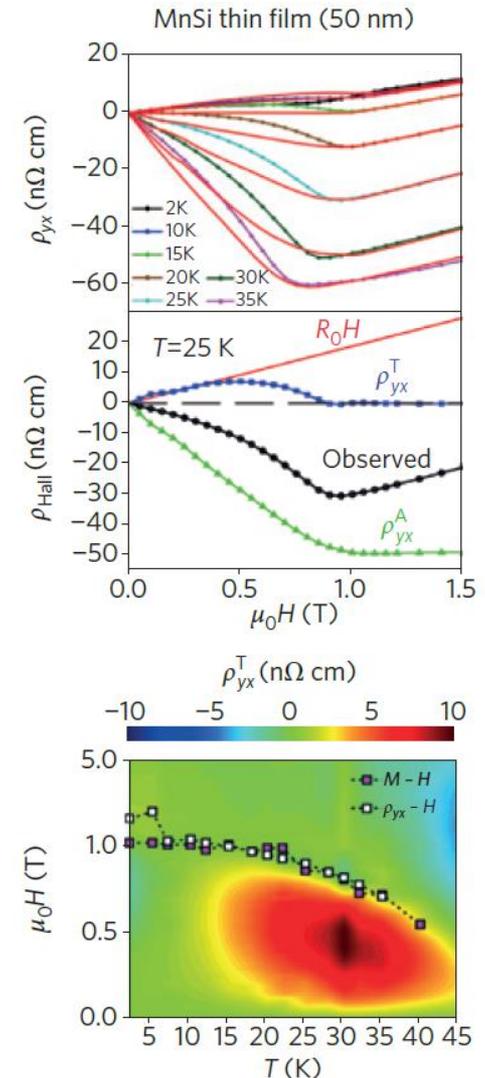


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- Skyrmion crystal leads to emergent magnetic field (B_{eff}^z)
- Skyrmion exerts one magnetic flux $\phi_0 = h/e$ on conduction electron – Topological Hall effect
- $B_{eff}^z = \phi_0(S/A)$
- $\rho_{xy} = \rho_{xy}^N + \rho_{xy}^A + \rho_{xy}^T$
- $\rho_{xy} = R_0 B + \mu_0 R_S M + P R_0 B_{eff}^z$



Nagaosa, Nature Nanotechnology 8 (2013)



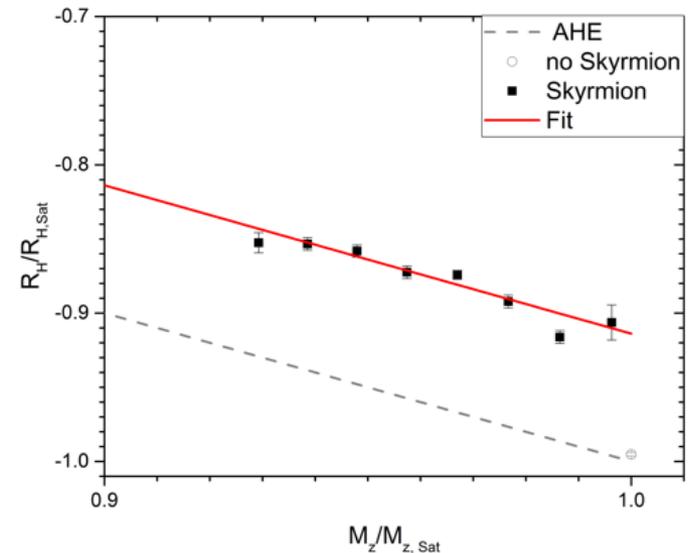
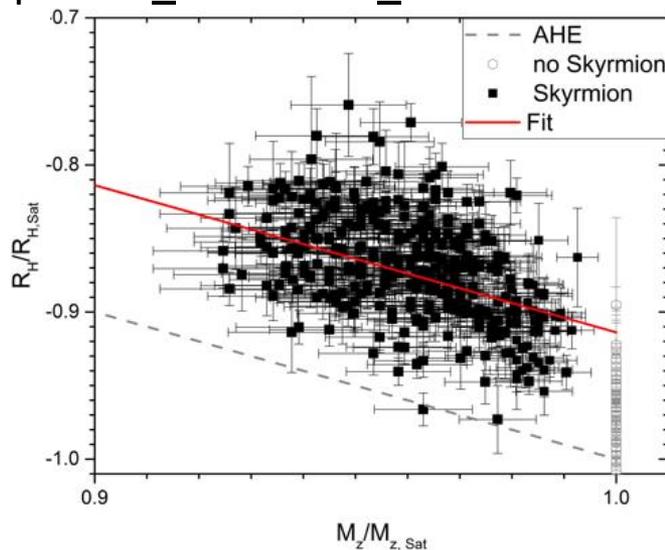
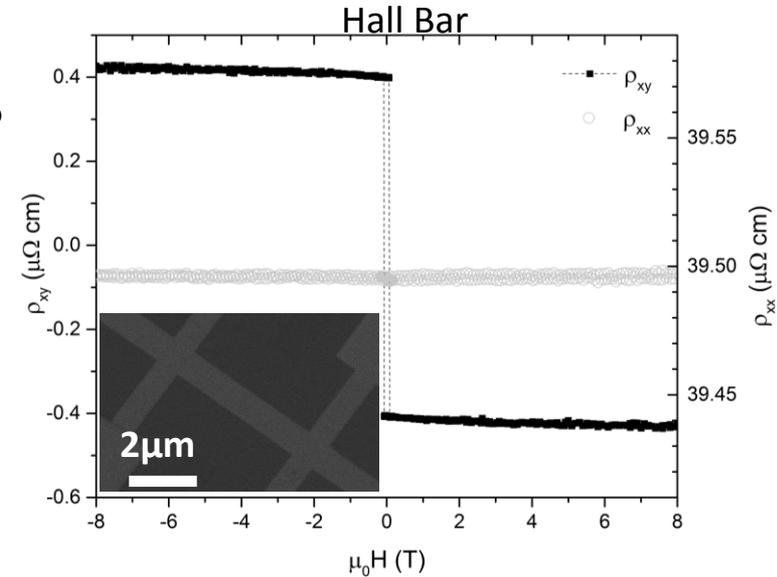
YuFan Li, PRL 110, 117202 (2013)

Topological Hall Resistance?



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- $\rho_{xy} = R_0 B + \mu_0 R_S M + P R_0 B_{eff}^z$
- What is the expected Topological Hall resistivity?
- Hall Bar \rightarrow Ordinary Hall coefficient
- $R_0 = -(1.9 \pm 0.2) \times 10^{-11} \text{ } \Omega\text{m/T}$.
- $\rho_{xy}^T = P R_0 \phi_0 (S/A) \approx 0.003 \text{ n}\Omega \text{ cm}$
- Can we separate out topological contribution?
- $R_{xy} - R^N = R_H = R^A + R^T$
- $R^A \propto M_z \rightarrow$ plot R_H vs $M_z \rightarrow$ Intercept $\propto R^T$
- Slope = -1.1 ± 0.1
- Intercept = $8.2 \pm 0.5 \% = 11 \pm 1 \text{ n}\Omega \text{ cm}$



Conclusion



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- Ta(3.5 nm)/Pt(3.8 nm)/
[Co(0.5 nm)/Ir(0.5 nm)/Pt(1.0 nm)]_{x10} Pt(3.2 nm)
- Can nucleate skyrmions with combination of current and magnetic field
- Influence skyrmion with field
- Observe Hall signature
- Up to 12 % change from saturated state
- Magnetisation independent contribution to Hall resistance
- 11₋₁+1 nΩ cm versus predicted 0.003 nΩ cm
- ArXiv 1706.06024

